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Internal and external conversion studies on the decay of Bi^{203} and Bi^{204}

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With 6 figures in the text

ABSTRACT

The internal K-conversion coefficients of 7 transitions following the decay of Bi^{203} (including the 279.1 keV transition in Tl^{203}) and 5 transitions from the decay of Bi^{204} have been determined absolutely by the method of comparing internal and external conversion lines measured in a double-focusing spectrometer. The multipolarity assignments based on these values are, in cases where a comparison is possible, in agreement with the assignments suggested from the measured internal conversion ratios or other data.

Complementary measurements of energies and intensities of low-energy conversion lines in Pb^{203} were carried out in the double-focusing spectrometer. The level scheme of Pb^{203} is discussed.

The half-lives of Bi^{203} and Bi^{204} have been remeasured and found to be (11.76 ± 0.05) h and (11.22 ± 0.10) h, respectively.

Introduction

The decays of Bi^{203} and Bi^{204} have earlier been beta-spectroscopically investigated by Novakov *et al.* [1] and Stockendal *et al.* [2], respectively, and by Fritsch and Hollander [3]. Because of the complexity of the decays, further studies were recommended so that more definite conclusions could be drawn about the level schemes, which are of great theoretical interest. In the present contribution, interest has been focused on the multipolarity assignments, with emphasis on the transitions in the Bi^{203} decay. Of greatest importance here has been the recently developed method for the absolute determination of internal conversion coefficients by the comparison of conversion lines and photolines (Hultberg and Stockendal [4]).

I. Experimental procedures and results

The Bi^{203} and Bi^{204} sources were produced by bombarding radiogenic lead with 35–55 MeV protons for a few hours in the synchrocyclotron of the Gustaf Werner Institute for Nuclear Chemistry in Uppsala. Both isotopes were always present in the sources, their mutual ratio depending on the proton energy used. The method used for separating the bismuth from the target material and for preparing the beta-spectrometer sources has been described earlier [5]. The dose rates from the samples used in the external conversion measurements were in all cases about 1 r/h at 20 cm immediately after preparation.

1. *Half-life measurements*

Since the conversion-line measurements described below sometimes had to be extended over a period long compared to the half-lives of Bi^{203} and Bi^{204}, considerable errors could have been introduced by using inaccurate values for the decay corrections. The best values earlier reported are:

$$T_{1/2}(\mathrm{Bi}^{203}) = \begin{cases} (12.3 \pm 0.7)\ \mathrm{h} & [5] \\ (11.5 \pm 1.0)\ \mathrm{h} & [3] \\ (12 \ \ \pm 1\ \ )\ \mathrm{h} & [6] \end{cases}$$

and

$$T_{1/2}(\mathrm{Bi}^{204}) = \begin{cases} (11.6 \pm 0.2)\ \mathrm{h} & [7] \\ (11.0 \pm 0.5)\ \mathrm{h} & [3]. \end{cases}$$

Since more accurate values would be desirable, a redetermination was carried out. The K-conversion lines of the 825.2 keV transition of Bi^{203} and the 671.0 keV transition of Bi^{204} were measured in a double-focusing spectrometer [8], and their decays were followed during about 8 and 6 half-lives, respectively. In Fig. 1 the peak counting rates over background, registered with a crystal detector (cf. ref. [9]), have been plotted in a semi-logarithmic diagram. The half-life values obtained from the straight lines are:

$$T_{1/2}(\mathrm{Bi}^{203}) = (11.76 \pm 0.05)\ \mathrm{h}$$

and

$$T_{1/2}(\mathrm{Bi}^{204}) = (11.22 \pm 0.10)\ \mathrm{h}.$$

2. *Absolute determination of internal conversion coefficients*

a. *Measurements*

The method applied in the present work for determining internal conversion coefficients absolutely by comparing conversion lines and photolines has been previously described in detail by Hultberg and Stockendal [4, 9, 10]. The experiments were carried out in the same double-focusing spectrometer [8] as was used in the works quoted. Various combinations of sources and uranium converters were used. In one case the source and converter were circular with 5 and 13 mm diameters, respectively. In four other cases rectangular sources and converters were used. The dimensions in the latter cases varied from one experiment to the other but were of the order of 3×12 mm² for the source and 13×20 mm² for the radiator. All sources and converters were plane. Two converter thicknesses were used, 2.19 and 3.86 mg/cm² U. The absorbers used between the sources and converters were made of 1.1 and 1.9 mm aluminium.

The procedure for the measurements was always the following. Firstly, the photoline spectrum was measured. Secondly, the uranium converter and aluminium absorber were removed and the internal conversion-line spectrum was measured. Thus

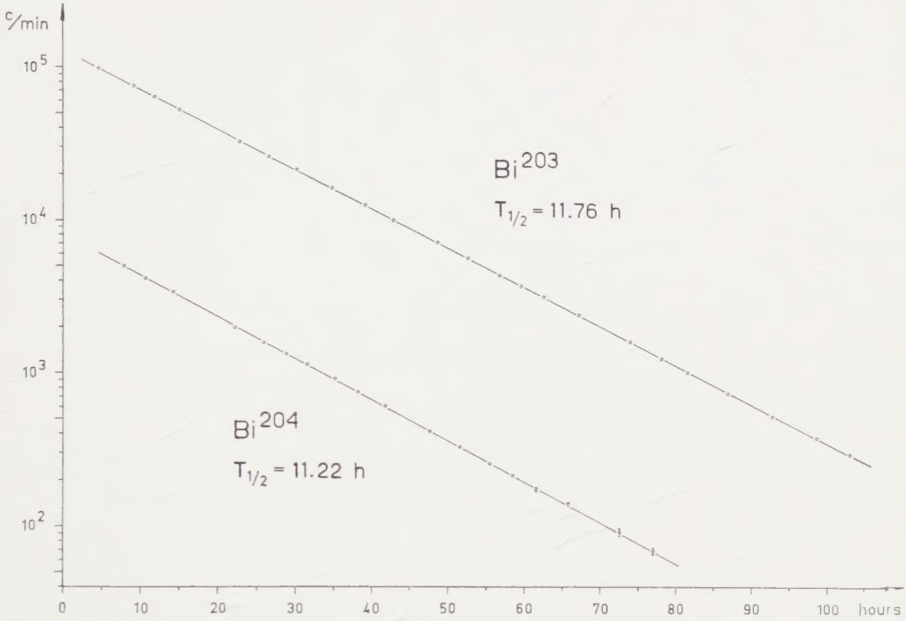

Fig. 1. Decay curves of K 825.2 of Bi^{203} and K 670.7 of Bi^{204}, as measured in a double-focusing beta spectrometer. A crystal detector was used.

the same source was used in both runs. Because of the high counting rates in internal conversion, a scintillation detector [9, 11] had to be used. In most cases the measurements were repeated several times. The spectrometer was adjusted to relative half-widths varying between 0.5 and 1 %. Some typical curves are shown in Figs. 2 and 3.

b. *Analysis of results*

According to ref. [4] the K-conversion coefficient can be calculated from the following formula:

$$\varepsilon_K = \frac{A_\beta}{A_\gamma}\,\tau_K\,f\,d\,b,$$

where ε_K = internal K-conversion coefficient,
A_β = recorded intensity of internal K-conversion electrons,
A_γ = recorded intensity of K-photoelectrons,
τ_K = tabulated value of photoelectric cross-section for the K-shell [12],
f = correction factor for τ_K (see refs. [4] and [10]),
d = converter thickness,
b = dimension factor (see refs. [4] and [10]).

The different f factors were found by interpolation from the values at the K-threshold energy (cf. [4]) and at the gamma-ray energies 412, 662 and 1332 keV.

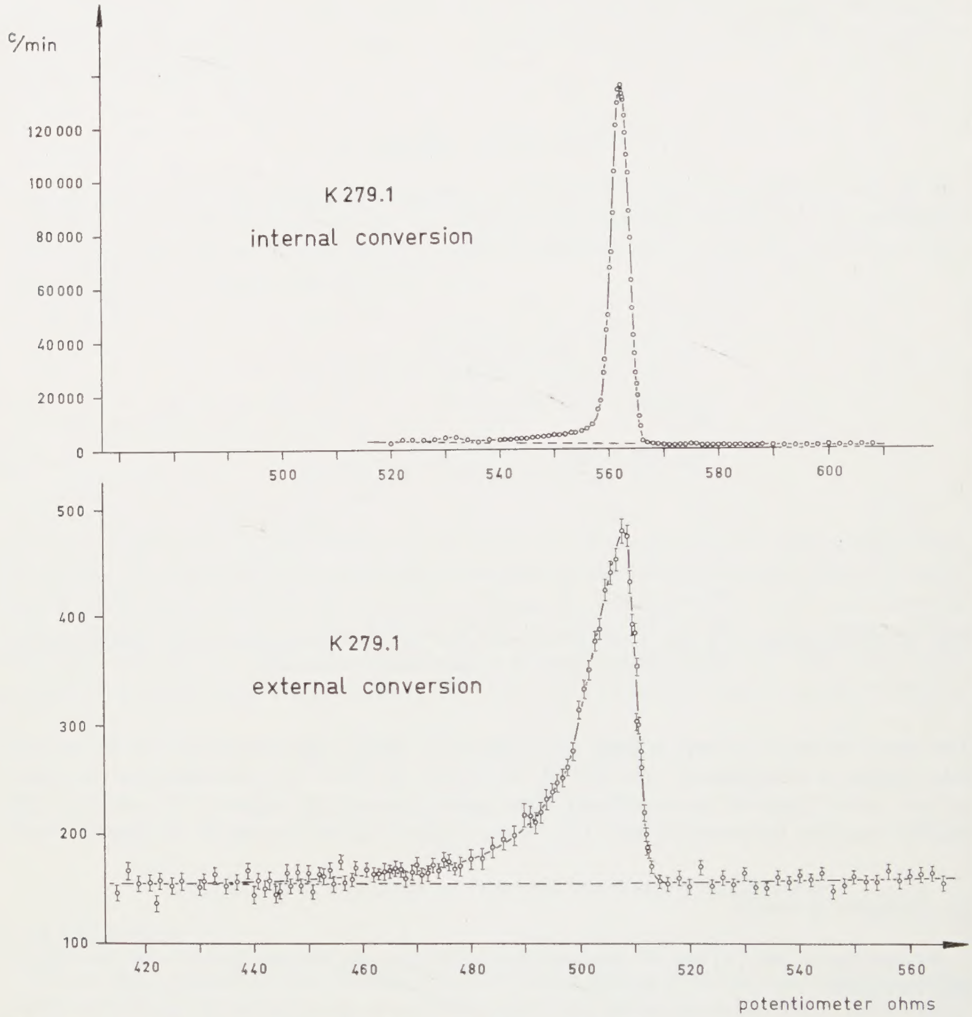

Fig. 2. The 279.1 keV transition in Tl^{203}, recorded with a plastic scintillator, in internal and external conversion. A 3.86 mg/cm² uranium converter was used in the latter case. The same source of Pb^{203} (Bi^{203}) was used in both measurements. The experiments were carried out in a double-focusing spectrometer. The lines shown have not been corrected for decay.

The calculations of the latter values for the appropriate source-converter geometry were made using the electronic computer BESK. The finite dimensions of the source were taken into account. The calculations were based on the experimental numerical values of the photoelectric angular functions given by Hultberg [10]. These functions represent "true" distributions, i.e. $\vartheta_0 = 0$, $d = 0$ (cf. ref. [10]). It was checked in one case that the error introduced by using these distributions instead of those for the appropriate d value was negligible ($< 0.5\,\%$).

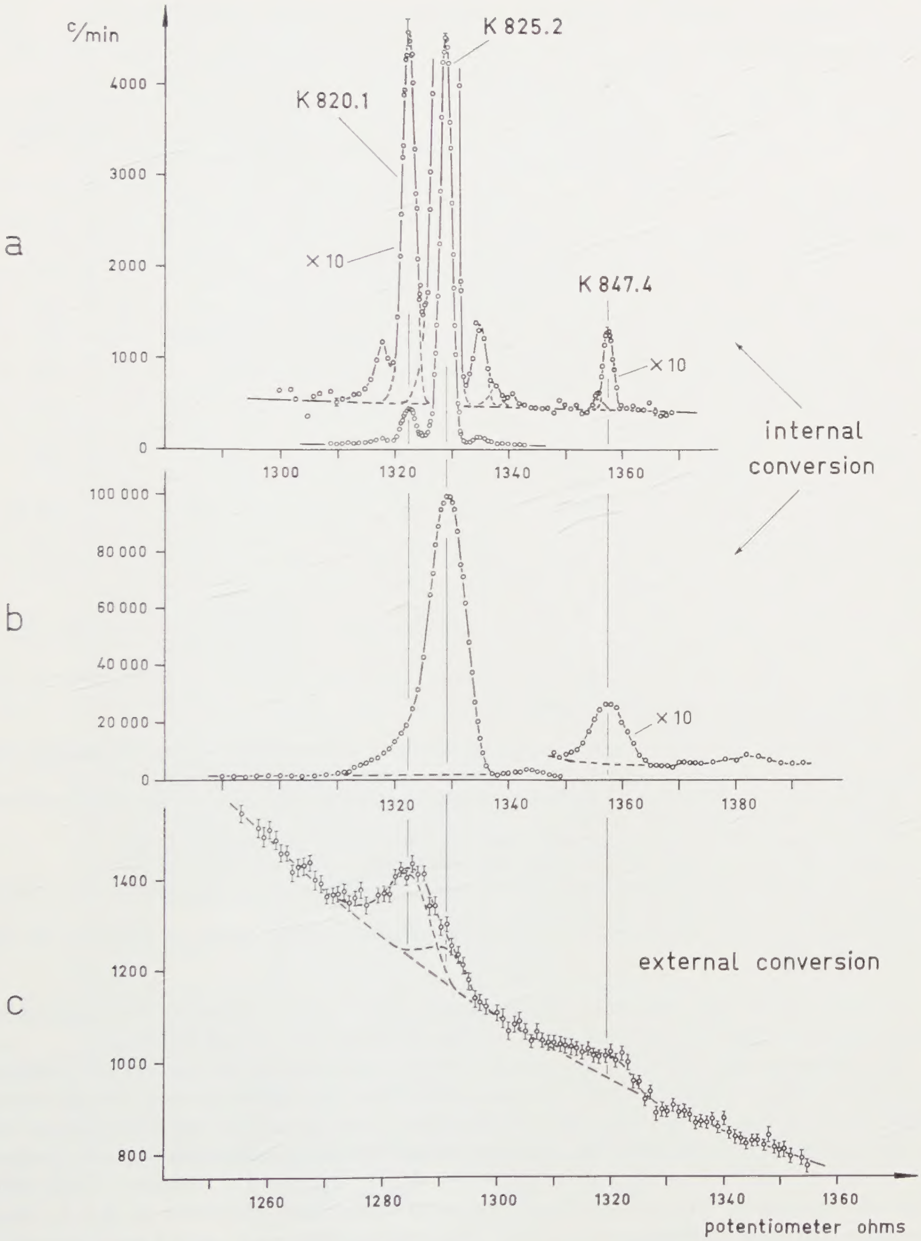

Fig. 3. A difficult case of conversion coefficient determination: the 820.1 keV ($E2$), 825.2 keV ($M4$) and 847.4 keV ($E2$) transitions in Pb^{203}. (*a*) Internal conversion spectrum obtained in a double-focusing spectrometer at about 0.18 % resolution. (*b*) and (*c*) Typical internal and external conversion lines used for the determination of ε_K. The same source and the same slit-setting of the double-focusing spectrometer (about 0.55 %) was used in these two measurements. Converter: 3.86 mg/cm² uranium. Decay corrections have not been made.

Table 1. Result of internal conversion coefficient measurements.

Nuclide	Transition energy (keV)	Relative gamma-ray intensity I_γ ($I_{\gamma\,825.2} = 100$; $I_{\gamma\,374.7} = 100$)	Internal K-conversion coefficient ε_K		Multi-polarity
			Experimental	Theoretical (Sliv and Band)	
Pb^{203} (a)	186.5	< 75	> 0.45	1.3	$M1$ (d)
	263.9	34 27 (c)	0.53 ± 0.10 0.67 ± 0.10 (c)	0.51	$M1$
	381.4	45	$(3.5 \pm 1.0) \times 10^{-2}$	3.7×10^{-2}	$E2$
	820.1	240	$(8.3 \pm 0.8) \times 10^{-3}$	7.8×10^{-3}	$E2$
	825.2	100	0.24 ± 0.05 (e)	0.22	$M4$
	847.4	68 (f)	$(6.7 \pm 2) \times 10^{-3}$ (f)	7.3×10^{-3}	$E2$
Pb^{204} (b)	289.3	4.8	0.37 ± 0.10	0.38	$M1$
	374.7	100	$(4.2 \pm 0.5) \times 10^{-2}$	3.9×10^{-2}	$E2$
	670.7	< 35	$> 2.3 \times 10^{-2}$	4.1×10^{-2}	$M1$ (g)
	899.2	120	$(8.3 \pm 1.0) \times 10^{-3}$	6.5×10^{-3}	$E2$
	911.7	28	$(5.4 \pm 1.2) \times 10^{-2}$	5.4×10^{-2}	$E5$
Tl^{203}	279.1		0.16 ± 0.015 (h)	0.08 ($E2$) 0.40 ($M1$)	$M1 + E2$

[a] Transition energies from Table 2 and ref. [1].

[b] Transition energies from ref. [2].

[c] The 170.2 keV $M1$ or $E1$ transition in Pb^{204} interferes in the measurements. The upper value corresponds to an $M1$ assignment of this transition, the lower value to an $E1$ assignment.

[d] $E1$ and $E2$ excluded from the ε_K measurement. Conclusive evidence for $M1$ is obtained from internal conversion ratios (see Table 2).

[e] By studying Pb^{204m} the value 0.23 ± 0.02 has been found (see Section I,2,d).

[f] Value may be somewhat influenced by the 846.1 keV transition in Pb^{204}.

[g] $E1$ and $E2$ excluded from ε_K measurement. The $M1$ assignment is suggested from internal conversion ratios and scintillation spectrum [1].

[h] In agreement with values obtained from observations on the β^- decay of Hg^{203} (cf. ref. [13] and Section I,2,c).

In cases where a K-photoline of one gamma ray was mixed with the L-photoline of another gamma ray, use was made of the relation $\tau_K/\tau_L = 5.3 \pm 0.2$ [10].

The experimental values of ε_K and I_γ (relative gamma-ray intensity) are included in Table 1. They are the weighted mean values from the different runs. Small corrections due to gamma-ray absorption in the aluminium placed between the source and converter have been applied. The errors indicated for the ε_K values have been obtained by quadratic addition of the uncertainties in A_β/A_γ, τ_K, f and d. Because of the different line intensities and possible interference of other lines, the error in A_β/A_γ varies strongly from one transition to another. The uncertainties in τ_K and f are taken to be 6 % and 5 %, respectively, in accordance with refs. [4] and [9]. However, for the transitions with energies below 300 keV, larger errors in f have been allowed for. The uranium thicknesses d were determined by two independent analysis procedures. Both methods were considered to be accurate to better than 1 %, and the results were in very good agreement. The error in d should therefore not be more than 1 %.

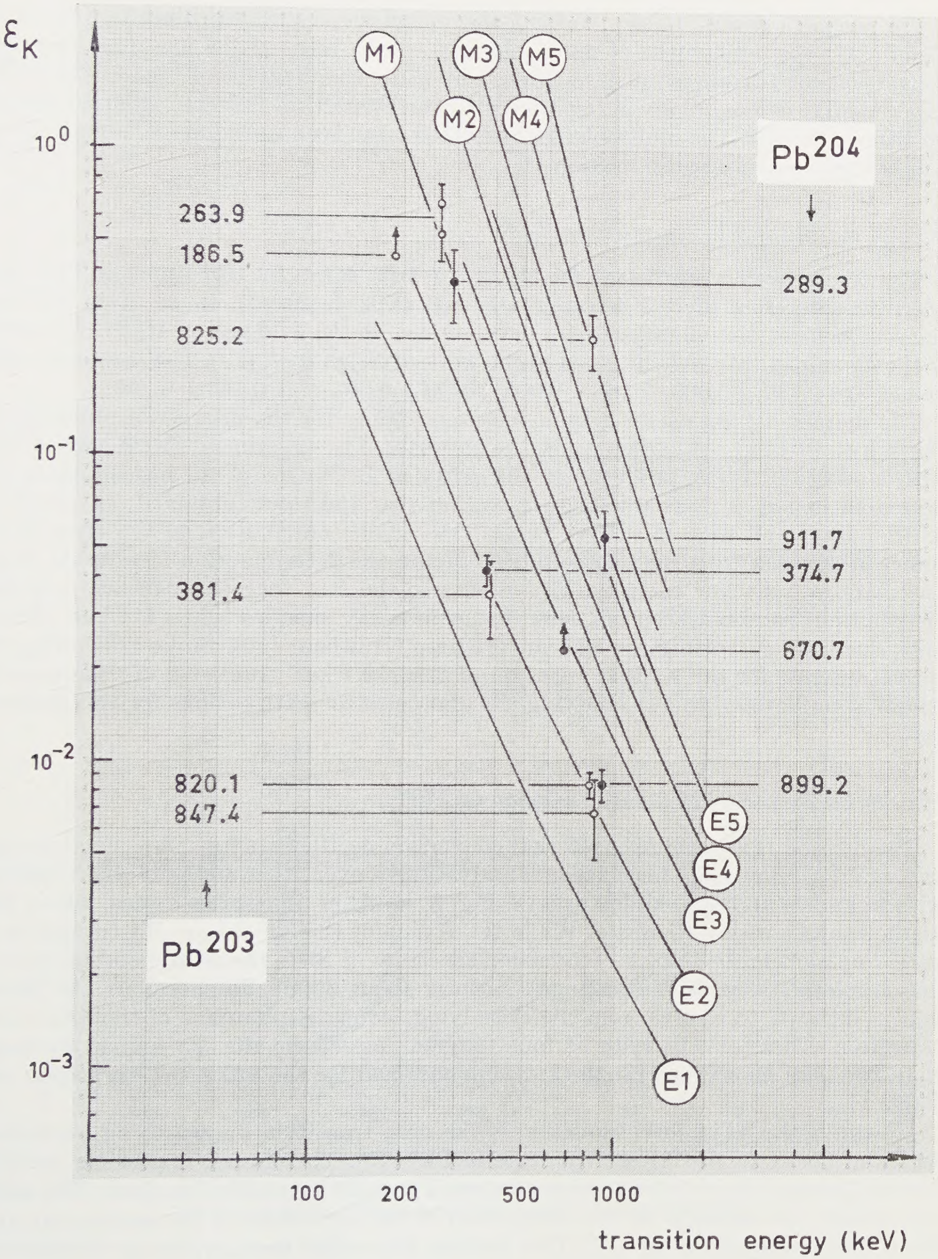

Fig. 4. Experimental conversion coefficients ε_K of transitions in Pb^{203} (circles) and Pb^{204} (points), in comparison with the theoretical values for $Z = 82$ according to Sliv and Band (curves). The arrows for the 186.5 and 670.7 keV transitions indicate lower limits of ε_K.

For comparison with theory, Table 1 also includes ε_K values calculated by Sliv and Band [14]. The assignment of multipolarities on the basis of the measured internal conversion coefficients is much facilitated by using the diagram of Fig. 4, where the experimental points are given together with the theoretical lines for different multipolarities ($Z = 82$). The multipolarities assigned have been included in Table 1. They will be further discussed in Section II.

c. ε_K *of the 279.1 keV transition in* Tl^{203}

The K-conversion coefficient for the 279.1 keV $M1 + E2$ transition in Tl^{203} has been the subject of several investigations (about 15 reported). In all cases but one the results have been obtained from observations on the β^- decay of Hg^{203}. A survey of the experimental results is given in the work of Nijgh *et al.* [13]. The most accurate values are 0.147 ± 0.002, 0.163 ± 0.003, 0.159 ± 0.004 and 0.163 ± 0.006.

The present determination was undertaken mainly for the interest in obtaining a check by a method not earlier applied to this case. The experiments were carried out with a source of Pb^{203}, produced in the decay of Bi^{203}. One of the measurements is presented in Fig. 2. It is satisfactory to find that the result obtained, $\varepsilon_K = 0.16 \pm 0.015$, agrees well with the above values. The main contribution to the error in ε_K comes in this case from the photoelectric f factor, the determination of which is more uncertain at very low energies. This is due to the fact that photoelectric angular distributions have not been measured for gamma-ray energies below 412 keV. However, such measurements are now in progress (Hultberg [15], Sujkowski [16]). Of special interest for the ε_K determination of the 279.1 keV transition are the experiments of Sujkowski, who is studying the photoelectric distributions for this gamma ray.

d. ε_K *of the isomeric 825.2 keV transition in* Pb^{203}

The method of determining internal conversion coefficients by comparing internal and external conversion lines has great advantages over other methods when dealing with unknown and/or complex decays. Fig. 3, however, illustrates a case, where the method meets with difficulties. While the K-line of the 825.2 keV $M4$ transition is very dominant in the internal conversion spectrum of Bi^{203}, the corresponding photoline is relatively weak (the intensity ratio is about 3000). Furthermore, the latter line is difficult to resolve from the close-lying, strong K-photoline of the 820.1 keV transition. Therefore, in spite of four different measurements, no higher accuracy than 20 % can be claimed for the ε_K value obtained for the 825.2 keV transition (cf. Table 1).

However, the 825.2 keV transition is the only transition known to be associated with the decay of the 6.1 sec $i_{13/2}$ state in Pb^{203} [5]. Therefore it is possible, for this special gamma ray, to find a more accurate ε_K value by another method. The most convenient one seems to be the comparison of the intensities of the gamma ray and the corresponding K X-ray [17]. This method has earlier been applied by Stockendal *et al.* to this very case [5]. A Bi^{203} activity was absorbed on an ion-exchange column and the scintillation spectrum of the milked-out activity was measured. Because of the lack of suitable equipment, however, only a lower limit of about 0.2 was found for the K-conversion coefficient from this experiment. A remeasurement with an improved technique was therefore recently carried out by Persson and Stockendal

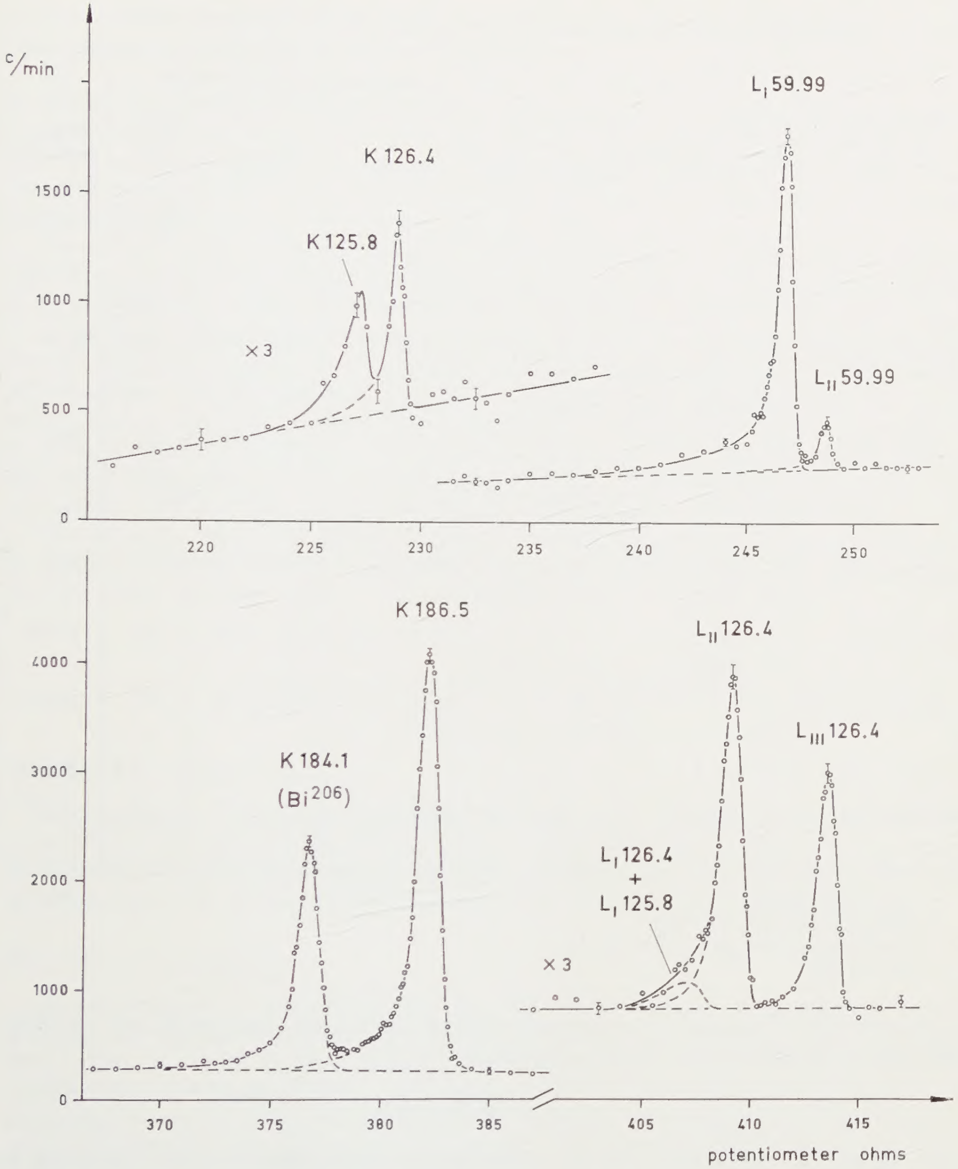

Fig. 5. Some of the internal conversion lines measured in a double-focusing spectrometer at about 0.3 % resolution. Decay corrections have not been applied.

[18]. The pulses from the scintillation counter were simultaneously fed into two 100-channel pulse-height analyzers. By using different amplifications the X-ray spectrum could be measured with great precision in one analyzer, while the photopeak

Table 2. Internal conversion lines studied in the decay of Bi^{203}.

Adopted transition energy (keV)	Internal conversion lines measured	Relative conversion line intensity ($I_{K\,825.2} = 100$)	Internal conversion ratios			Multipolarity
			Ratio	Experimental	Theoretical (Sliv and Band)	
59.99 ± 0.03	L_{I} 59.99, 59.99	57.8 ± 4	$L_{\mathrm{I}}/L_{\mathrm{II}}$	9.2 ± 1.0	9.5	$M1$
	L_{II} 59.96	6.3 ± 0.6	$L_{\mathrm{III}}/L_{\mathrm{II}}$	< 0.2	0.088	
126.4 ± 0.1	K 126.4	9.4 ± 1.0	$K/\Sigma L$	0.17 ± 0.02	0.28	$E2$
	L_{II} 126.3, 126.4	31.9 ± 2.5	$L_{\mathrm{I}}/L_{\mathrm{II}}$	< 0.16	0.078	
	L_{III} 126.2, 126.4	22.6 ± 2	$L_{\mathrm{II}}/L_{\mathrm{III}}$	1.41 ± 0.11	1.38	
186.5 ± 0.1	K 186.3, 186.5	141 ± 7	$K/\Sigma L$	5.8 ± 0.4	5.6	$M1$
	L_{I} 186.4, 186.5	21.7 ± 2	$L_{\mathrm{I}}/L_{\mathrm{II}}$	8.7 ± 1.5	9.4	
	L_{II} 186.5	2.5 ± 0.4	$L_{\mathrm{I}}/L_{\mathrm{III}}$	> 20	125	
	M_{I} 186.6	8.7 ± 1.5	$(L_{\mathrm{I}} + L_{\mathrm{II}})/\Sigma M$	2.8 ± 0.5		
263.9 ± 0.2	K 263.9, 264.0	75.3 ± 5	$K/(L_{\mathrm{I}} + L_{\mathrm{II}})$	5.2 ± 0.5	5.7	$M1$
	L_{I} 263.9	14.5 ± 2 (a)				
820.1 ± 0.5	K 820.1	8.3 ± 0.6	$K/(L_{\mathrm{I}} + L_{\mathrm{II}})$	4.9 ± 1.0	4.8	$E2$ (c)
	L_{I} 820.2	1.7 ± 0.4 (a)				
825.2 ± 0.5 (b)	K	100	$K/(L_{\mathrm{I}} + L_{\mathrm{II}})$	3.7 ± 0.3	3.7	$M4$ (c)
	$L_{\mathrm{I}}\,L_{\mathrm{II}}$	27.2 ± 2.5				
847.4 ± 0.5	K 847.4	1.9 ± 0.2				$E2$ (c)
1033.8 ± 1.0	K 1033.8	3.4 ± 0.3	$K/\Sigma L$	> 4.8	5.6	$M1$ (d)
	L_{I}	< 0.7				

[a] $(L_{\mathrm{I}} + L_{\mathrm{II}})$ intensity.
[b] Energy value from ref. [5].
[c] Unambiguously suggested in Table 1.
[d] See ref. [1].

of the 825.2 keV gamma ray was recorded in the other one, (for details, see ref. [18]). The result obtained from this measurement is

$$\varepsilon_{K\,825.2} = 0.23 \pm 0.02.$$

This should be compared with the experimental value of 0.24 ± 0.05 obtained by the method of external conversion, and with the theoretical value of 0.22 given by Sliv and Band [14] for an $M4$ transition of this energy.

3. *Internal conversion lines in the decay of Bi^{203}*

In order to compensate for the lack of multipolarity information in some cases, due to difficulties in determining ε_K, and in order to check and complement earlier data, some special internal conversion-line measurements were carried out in the double-focusing spectrometer at higher resolution. Interest was focused on the transitions associated with the lower levels in Pb^{203}.

Fig. 5 shows parts of the spectrum measured with the spectrometer adjusted to a relative half-width of about 0.3 %. A G.M. tube, having a mylar window with a cut-off energy measured to be (15.4 ± 0.4) keV, was used as the electron detector. The lowest energy region shown in Fig. 5 had earlier been studied only in a permanent magnet spectrometer. The K line of the 126.4 keV transition and the L_{II} line of the 59.99 keV transition were previously not observed.

Table 2 gives the measured energies and intensities of the Bi^{203} transitions studied. The energy calibration was made using the (184.1 keV ± 0.1) keV transition in Pb^{206} [19], the (279.12 ± 0.05) keV transition in Tl^{203} [20] and the (825.2 ± 0.5) keV transition in Pb^{203} [5]. Small intensity corrections were made in accordance with the results of Bergkvist [21] on relative intensity measurements in the double-focusing spectrometer. The K 126.4 and L 59.99 lines had also to be corrected slightly due to absorption in the G.M. window [22]. The energy and intensity values are mostly in good agreement with those given by Novakov *et al.* [1]. For the conversion lines of the 126.4 and 186.5 keV transitions, however, the latter intensity values are considerably lower due to a systematic error in the measurements of these lines.

The internal conversion ratios found for the different transitions are also included in Table 2 together with the theoretical values of Sliv and Band [14]. The multipolarities based on these ratios are given as well.

II. Discussion of multipolarity assignments

1. *Transitions in* Pb^{203}

The 59.99 keV transition

A comparison with theory [14] shows that the only multipolarity assignment consistent with the experimental limit $L_{III}/L_{II} < 0.2$ is $M1$. Furthermore, the measured L_I/L_{II} ratio is in good agreement with this assignment (see Table 2). It can therefore be unambiguously concluded that this transition has mainly multipolarity $M1$.

The 126.4 keV transition

On the basis of the measured $(L_I + L_{II})/L_{III}$ ratio, Novakov *et al.* suggested multipolarity $E2$ for this transition [1]. This assignment is verified by the L-subshell ratios given in Table 2, since for all other multipolarities the theoretical values lie outside the experimental limits. The measured $K/\Sigma L$ ratio, however, is found to be somewhat lower than the theoretical value for $E2$. Nevertheless it is clear that no other multipolarity fits the experimental values better than $E2$.

In a very recent study of delayed coincidences, Bergström *et al.* found that the 126.4 keV transition is associated with a half-life of (55 ± 5) mμsec [23]. On comparison with the theory for single particle transitions [24], one finds that this half-life is in good agreement with an $E2$ assignment.

The 186.5 keV transition

The experimental $K/\Sigma L$ ratio, 5.8 ± 0.4, definitely excludes all multipolarities except $M1$ and $E1$ for this transition (cf. the theoretical values are 5.6 and 5.5, respectively [14]). The measured, relative L-subshell intensities, however, are not compatible with the theoretical conversion coefficients for $E1$ [14], whereas good agreement is obtained for $M1$ (cf. Table 2). Thus it must be concluded that the transition has mainly $M1$ character, as earlier suggested [1].

Regarding the ε_K measurement in this case, the K-photoline falls in the region of the KLL Auger lines of uranium. Therefore only a lower limit could be obtained for the K-conversion coefficient (cf. Table 1). As can be seen in Fig. 4, this limit excludes the multipolarities $E1$ and $E2$, and is in agreement with the $M1$ assignment made.

The 263.9 keV transition

The measured $K/(L_\mathrm{I}+L_\mathrm{II})$ ratio, 5.2 ± 0.5, indicates that this transition has mainly magnetic dipole character (cf. the nearest theoretical values [14]: 4.1 ($M2$), 5.7 ($M1$), and 6.5 ($E1$)). This is strongly supported by the experimental information about ε_K (see Table 1). In the calculation of ε_K, allowance had to be made for the L 170.2 (Pb^{204}) line, which coincides with the K-photoline of the 263.9 keV transition. Depending on which of the two possible multipolarity assignments, $M1$ or $E1$ [2], is chosen for the 170.2 keV transition, $\varepsilon_{K\,263.9}$ is found to be 0.53 ± 0.10 or 0.67 ± 0.10, respectively. The former value agrees very well with an $M1$ assignment, while the latter value is slightly too large (cf. Table 1 and Fig. 4).

In the internal conversion spectrum, a line has been found which might be interpreted as the L_III line of the 263.9 keV transition. Its intensity is about 10 % of the $(L_\mathrm{I}+L_\mathrm{II})$ intensity. This would suggest multipolarity $M2$, or $M1$ with a large $E2$ admixture. Both of these possibilities, however, are in disagreement with the experimental data of ε_K and/or $K/(L_\mathrm{I}+L_\mathrm{II})$. Therefore it is probable that the "L_III line" belongs to another transition.

Earlier suggestions of multipolarity for the 263.9 keV transition are $M1$ [1] and $M1$ or $M2$ [3].

The 381.4 keV transition

As shown in Fig. 4, the experimental K-conversion coefficient unambiguously suggests multipolarity $E2$ for this transition. The internal conversion information is too poor for any conclusions to be drawn on the basis of conversion ratios.

The 820.1, 825.2 and 847.4 keV transitions

Typical internal and external conversion spectra of these lines are presented in Fig. 3. The spectra are characterized by the high conversion of the well-known $M4$ transition of 825.2 keV [5], and the diverging multipolarities of the 820.1 and 847.4 keV transitions, as compared to the $M4$ transition, are immediately indicated from the figure. The determined K-conversion coefficients given in Table 1 (from four independent measurements) verify the $M4$ assignment of the 825.2 keV transition, and show that both of the other transitions are mainly of multipolarity $E2$ (cf. Fig. 4). An uncertainty in the ε_K value of the 847.4 keV transition is due to a possible 846.1 keV transition (846.2 keV according to ref. [2]) in Pb^{204} (cf. the high-resolution run in Fig. 3). This, however, should not influence the multipolarity assignment made. The assignments of the 820.1 and 825.2 keV transitions are supported by the measured $K/(L_\mathrm{I}+L_\mathrm{II})$ ratios given in Table 2.

In the work of Novakov *et al.* [1] the 820.1 and 847.4 keV transitions were suggested to have multipolarity $M1$ ($+ E2$). The $E2$ admixtures had to be assumed with regard to the coincidence results and decay scheme. The present multipolarity assignments, however, lead to a still better understanding of the coincidence results, and also, considering the higher intensities found for the 126.4 and 186.5 keV transitions, of the decay scheme (see Section III).

The 1033.8 keV transition

The $K/\Sigma L$ ratio has been remeasured and is consistent with the $M1$ assignment previously suggested [1].

2. *Transitions in Pb^{204}*

The 289.3 keV transition

Internal conversion and scintillation measurements by Stockendal *et al.* indicate $M1$ character for this transition [2]. The experimental K-conversion coefficient, 0.37 ± 0.10, verifies this assignment (cf. the theoretical value is 0.38 [14]). The error of ε_K includes an uncertainty due to the interference of the weak 292.2 keV transition.

The 374.7 and 911.7 keV transitions

These transitions have earlier been studied in several investigations and their predominant $E2$ and $E5$ characters, respectively, are well established [25, 26, 27, 2]. The present absolute values of the K-conversion coefficients are further arguments for these assignments (the experimental values are $\varepsilon_{K\,374.7} = (4.2 \pm 0.5) \times 10^{-2}$ and $\varepsilon_{K\,911.7} = (5.4 \pm 1.2) \times 10^{-2}$; cf. the theoretical values are 3.9×10^{-2} and 5.4×10^{-2}, respectively [14]). Earlier experimental values are $\varepsilon_{K\,374.7} = (4 \pm 1.5) \times 10^{-2}$ and $\varepsilon_{K\,911.7} = (5 \pm 1) \times 10^{-2}$, as obtained from relative measurements using scintillation techniques (Maeder *et al.* [25]). Furthermore, the values of $(4.44 \pm 0.29) \times 10^{-2}$ and $(5.49 \pm 0.20) \times 10^{-2}$ have been found indirectly from a consideration of transition intensities in the decay of 68 min Pb^{204m} (Herrlander *et al.* [27]).

Regarding the purities of the multipolarities, Krohn and Raboy [26] found from angular correlation measurements that the 374.7 keV gamma ray is $E2$ with a 0.5 % mixture of $M3$, and that the 911.7 keV gamma ray is $E5$ with a 1 % mixture of $M6$. The former admixture cannot be excluded from the measured ε_K values, whereas, in the latter case, Herrlander *et al.* find a maximum admixture of 0.5 % $M6$ [27].

The 670.7 keV transition

Because of the weakness of the K-photoline of this transition, only a lower limit could be obtained for the internal K-conversion coefficient. However, this limit definitely excludes the multipolarities $E1$ and $E2$ (see Fig. 4). The same conclusion was earlier drawn from scintillation masurements [2]. Combined with the measured $K/\Sigma L$ ratio, these results indicate unambiguously that this transition has magnetic dipole character (cf. ref. [2]).

The 899.2 keV transition

As shown in Fig. 4, the most probable multipolarity assignment, based on the measured K-conversion coefficient, is $E2$, in agreement with earlier work [26, 27, 2].

The deviation between the experimental and theoretical values is, however, surprisingly large, with regard to the fact that this should be a pure $E2$ transition. Only one measurement was made of this conversion coefficient.

III. The level scheme of Pb^{203}

The emphasis in the present work has been laid on the transitions associated with the lower levels in Pb^{203}. A tentative level scheme was given by Novakov *et al.* [1], and Fig. 6 shows the lower part of this scheme with the changes and completions introduced which have been called for by the present results. The level sequence is unchanged. Some comments will here be made.

1. *Level energies*

The level energies are generally identical with the energies of the corresponding ground-state transitions (cf. Table 2). In the cases of the 186.4 and 1033.8 keV levels, the energies have been adopted as weighted mean values suggested by the following relations (in keV):

$$\left.\begin{array}{r} 60.0 + 126.4 = 186.4 \\ \\ \text{transition energy} = 186.5 \end{array}\right\} \qquad \left.\begin{array}{r} 60.0 + 126.4 + 847.4 = 1033.8 \\ 186.5 + 847.4 = 1033.9 \\ \text{transition energy} = 1033.8 \end{array}\right\}$$

The very good energy agreement lends strong support to the level scheme.

2. *Spin and parity assignments*

The 820.1 and 1033.8 keV states were previously assigned 7/2 – (or 9/2 –) and 5/2 – (or 7/2 –) [1]. The present investigation has shown, however, that the 820.1 and 847.4 keV transitions both have mainly $E2$ character (cf. Tables 1 and 2). Therefore the most probable spin and parity assignments should be 9/2 – for the 820.1 keV level and 7/2 – for the 1033.8 keV level. The assignments 7/2 – and 5/2 –, respectively, may not, however, be completely excluded (cf. the 703.3 keV level in Pb^{205} [28]).

With regard to the favoured 9/2 – assignment of the 820.1 keV state, the spin and parity of the 1084.0 keV state may be 9/2 – or 11/2 – (earlier assignment: 9/2 – [1]). As to the remaining states shown in Fig. 6, the assignments are the same as were given by Novakov *et al.* [1].

3. *Transition intensities*

At the head of the transitions in Fig. 6, the relative, total transition intensities are given in the intensity scale used in Table 2, i.e. $I_{K\,825.2} = 100$. The values have been calculated from the experimental internal conversion-line intensities using the theoretical conversion coefficients of Sliv and Band [14] ($I_M + I_N + \ldots = 0.3\, I_L$ has been assumed).

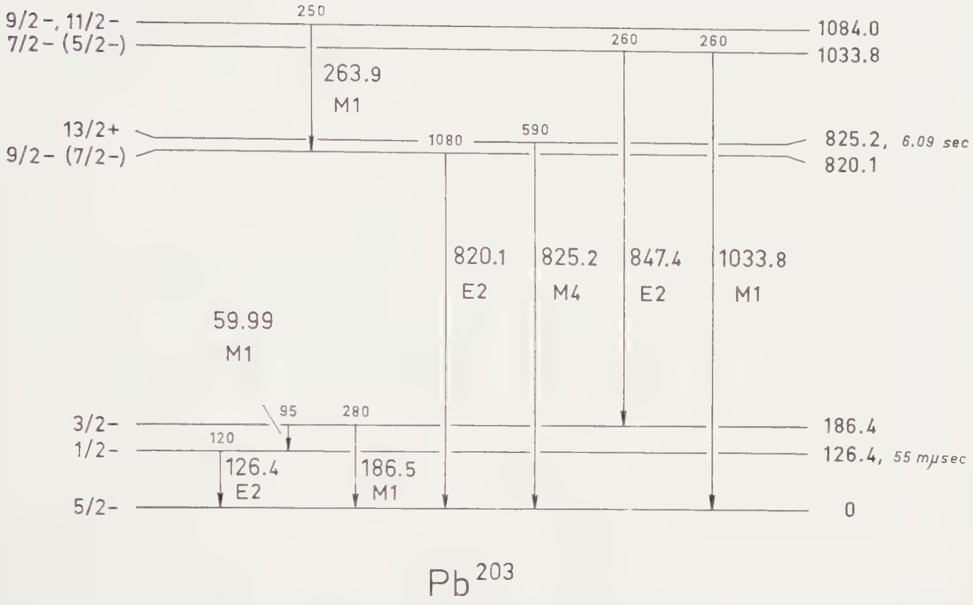

Fig. 6. Lower levels in Pb^{203} as populated in the electron-capture decay of 9/2 − Bi^{203}. (For higher levels, see the decay scheme of ref. [1].) The total transition intensities, indicated at the head of the transitions, are given in the intensity scale used in Table 2 ($I_{K\,825.2} = 100$). The separation between the levels of 825.2 and 820.1 keV is, for clarity, exaggerated. Experimental evidence indicative of a $13/2+ \rightarrow 9/2-$ $M2$ transition between these states, in analogy with the case of Pb^{205}, is discussed in the text.

An inspection of Fig. 6 shows that the proposed level scheme seems reasonable also from the point of view of transition intensities. Thus, for instance, the $\gamma(59.99)$–$\gamma(126.4)$ cascade, suggested from energy correspondence (see above), is supported by the reasonably good agreement between the total intensities of these two transitions ($I_{\text{tot}\,59.99} \sim 95$; $I_{\text{tot}\,126.4} \sim 105$ or ~ 120, depending on whether the K or L line intensities are used in the calculation of $I_{\gamma\,126.4}$). It is further indicated that, disregarding the levels of 825.2, 1033.8 and 1084.0 keV, direct feeding from the 9/2 − ground state of Bi^{203} [29], and or additional feeding from higher levels, takes place to the 186.4 and 820.1 keV levels.

4. *Gamma-transition probabilities*

In the cases where several gamma rays are emitted from the same state, it may be of interest to compare the experimental, relative gamma-transition probabilities with those obtained from the theory of Weisskopf for single-proton transitions [24]. Thus one finds, for the two $M1$ gamma rays emitted from the 186.4 keV level, that the experimental intensity ratio $I_{\gamma\,186.5}/I_{\gamma\,59.99}$ is approximately 10, while the theoretical ratio is about 30. Hence the agreement between experimental and theoretical values is good. This supports the order of emission suggested for the gamma rays of 59.99 and 126.4 keV. (The reversed order would not give good agreement with theory.)

In the case of the 847.4 keV $E2$ and 1033.8 keV $M1$ gamma rays emitted from the 1033.8 keV levels, the experimental intensity ratio of $I_{\gamma\,1033.8}/I_{\gamma\,847.4}$ is about 1. Using the value $r_0 = 1.20 \cdot 10^{-13}$ for the nuclear radius constant and neglecting the statistical factors S, the theoretical ratio is found to be approximately 800. The deviation between the experimental and theoretical values is, however, not considered serious in view of the experimental fact [30] that many $M1$ transitions are of the order of 100 times longer in mean life than estimated from the theory.

5. *The decay of the* $i_{13/2}$ *state*

It has earlier been established that the 6.09 sec $i_{13/2}$ state in Pb^{203} is de-excited by an $M4$ transition of 825.2 keV [5]. However, no other gamma rays of energy larger than 40 keV have been observed in the decay of this isomeric state [5, 18]. In this connection it may be useful to study the radial matrix elements M for the $i_{13/2} \rightarrow f_{5/2}$ transitions in the odd-mass lead isotopes. The following values of $|M|^2$ have been found [5, 31, 32]:

Pb^{197}: 3.8 ± 0.5

Pb^{199}: 3.8 ± 0.2

Pb^{201}: 3.5 ± 0.2

Pb^{203}: 4.3 ± 0.1

Pb^{207}: 3.7 ± 0.1

Since $M4$ transitions are known to be very regular in their behaviour, it is surprising to find that the accurately determined $|M|^2$ value for the $M4$ transition in Pb^{203} is about 15 % larger than the average of the other four values, which, within the experimental errors, are remarkably constant.[1]

The deviating matrix element in the Pb^{203} case seems to indicate that the depopulation of the $i_{13/2}$ state in this nucleus does not take place via the $M4$ transition alone, but, to about 15 %, also in a different way. The transitions associated with such a decay are expected to be highly converted, since no gamma rays other than that of 825.2 keV have been seen in a scintillation spectrum of Pb^{203m} ($E_\gamma > 40$ keV) [5]. The most plausible explanation[2] seems to be the assumption that a 5.1 keV $M2$ transition takes place to the 820.1 keV state ($9/2-$ most probable assignment). The decay of the $i_{13/2}$ state in Pb^{203} would then be analogous to the case of Pb^{205}. It has recently been found that, in the latter isotope, the $i_{13/2}$ state of 1013.8 keV decays by an $M2$ transition of 26.22 keV (to a $9/2-$ state of 987.6 keV), an $E3$ transition of 310.5 keV and an $M4$ transition of 1014.0 keV [28, 34]. Considering the half-lives, it seems quite reasonable to associate a 5.1 keV $M2$ transition with the 6.09 sec state in Pb^{203} (cf. the 26.22 keV $M2$ transition from the 4.0 msec state in Pb^{205}). The low energy of the former transition may explain why the $i_{13/2}$ state in Pb^{203} decays predominantly by $M4$ radiation, whereas, in the case of Pb^{205}, the main de-excitation takes place via the $M2$ transition (more than 97 %) [28].

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[1] It may be pointed out that a constancy of the matrix elements of $M4$ transitions has been reported also for other isotopes (see e.g. ref. [33]).

[2] The possibility that the isomeric state decays also by electron capture to an expected $h_{11/2}$ level in Tl^{203}, may be considered (cf. Pb^{195} and Pb^{197}, where such branches have been found [31]). However, a rough estimate of the gamma-ray intensities of the transitions expected in such a decay, shows that the anomalous matrix element in Pb^{203} can hardly be explained by this effect. Furthermore, a preliminary search for internal conversion lines of transitions following such a decay has given a negative result.

It would therefore be of great interest to search for internal conversion electrons ($M, N, O, \ldots$) in the energy region below about 5 keV. An electromagnetically isotope-separated Bi^{203} source should be used and, for comparison, also a source of another Bi isotope (cf. ref. [28]).

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ERRATUM

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Page 426 line 9: "for Pb^{206} 780 MeV" should be "for Pb^{206} 1140 MeV"